Cyclic analysis of RC frames with respect to employing different methods in the fiber model for consideration of bond-slip effect

Abstract

In this research, based on a nonlinear analysis of reinforced concrete moment-resisting frames, the bondslip effect between concrete and bars along the lengths of beam, column, and joint elements was applied to numerical equations. The governing theory in the numerical equations was similar to that of the fiber model, but the perfect bond assumption between the concrete and bar was removed. The precision of the proposed method in considering the real nonlinear behavior of reinforced concrete frames was compared to the precision of other suggested methods for considering the bond-slip effect in fiber model analysis. Among the capabilities of this method are its ability of modeling the embedded lengths of bars within joints and nonlinear modeling of bond-slip. The precision of the analytical results were compared with the experimental results achieved from 2 specimens under cyclic loading. The comparison showed that the proposed method can model the nonlinear behavior of reinforced concrete frames with very good precision.

Key Words: Bond-slip effect, pull-out effect, cyclic analysis, RC frames

Introduction

Many analytical models have been devised for the nonlinear analysis of reinforced concrete (RC) frames. Although 2-dimensional and 3-dimensional modeling in a finite element method can make for more accurate analysis, it considerably increases the expense and time of analysis. Therefore, such methods are typically used for modeling structural parts while easier methods are utilized for the full modeling of structures. The one-component model of Clough et al. (1965) is one of the simple models used for nonlinear analysis of RC frames. Various models with concentrated plasticity (Brancaleoni et al., 1983) were presented later and a more accurate description of the nonlinear behavior of the elements of RC frames became available through models with distributed plasticity (Soleimani et al., 1979). Other models (Filippou et al., 1992), including multispring models that use subelements, were devised. One of the most commonly used methods is the fiber model. In this method, an element is divided into a number of concrete and steel fiber lengths, and the element section specifications are worked out by adding up the effects of the fibers' behavior. This method assumes a perfect bond between concrete and bar (Spacone et al., 1996; Mazars et al, 2006), but this assumption is not very appropriate or realistic and causes a considerable difference between analytical and experimental results (Kwak and Kim, 2006). Belarbi and Hsu (1994), as well as Kwak and Kim (2002), made use of the fiber method, but in order to modify it and reduce the error of analysis resulting from the perfect bond assumption, they modified the stress-strain behavior of the bars. In this way, they drew on an equivalent method. Limkatanyu and Spacone (2002a) used the fiber model but removed the perfect bond assumption. In order to achieve this, they differentiated between the degrees of freedom of the concrete and of the bars in the beam-column elements. This modified method was used for beam-column elements in the present study, but for modeling RC frames, a joint element is also needed. What matters is the compatibility and assimilability of joint elements with beam-column elements. In initial methods of nonlinear analysis of RC frames, the nonlinear effect of beamcolumn joints is considered using calibration of plastic hinges within adjacent beam-column elements (Otani, 1974). In such a situation, the joint element is not modeled separately, but rather its effect on the adjacent elements is considered. From there, the joints of RC frames are located in critical zones and they are affected by different effects such as high shear force and the bond-slip effect, so the joints need more precise modeling (Lee et al., 2009). Based on another approach, the behaviors of each of the elements of joint, beam, and column are separated. The zero-length rotational spring is one such joint element (Alath and Kunnath, 1995). In this kind of modeling, the effect of shear deformation is considered using a spring whose governing behavior is moment-rotation. In another type, as in the previous approach, 2 springs are used in the joint modeling. In one spring, the effect of shear deformation is taken into account, and in the other, the effect of deformation resulting from bar slip is taken into account (Biddah and Ghobarah, 1999). In order to calibrate such joint elements, experimental results or estimated force-deformation relationships at the joints should be used, but a precise calculation of such relationships is not easy, especially in structures that enjoy a high multiplicity of joint element types. Moreover, in such cases, various factors affecting the nonlinear behavior of joints are not separated but are generally applied in the models. In some newer methods, joint elements are modeled as 2-dimensional planes, but in order to use such elements along with adjacent beam-column elements in assembling

the whole of the RC frame, transient elements are also utilized so that there will be a connection between the degrees of freedom of joint plane and of adjacent linear elements (Elmorsi et al., 2000). Such elements typically have 2-dimensional formulations and are capable of separately modeling the behavior of concrete and bars and the interactions between them. These elements, however, like finite element methods, increase the modeling time and the amount of calculations. Furthermore, when there is a need for the degrees of freedom of the concrete and bars in the joint element to be compatible with the corresponding degrees of freedom in the adjacent linear beam-column elements, this type of modeling has its own limitations. Another type of joint element is created by assembling a series of one-dimensional components that are used for modeling the dominant behavior of joint elements and whose calibration is carried out through experimental results (Lowes et al., 2004). This kind of modeling relies on the behavior of force deformation for each effective component, and because force-deformation relations are calculated approximately, such modeling will not be completely precise and will need a strong calibration process. Limkatanyu (2000) introduced an interior joint element based on the separation of the degrees of freedom of bars going through the joints and concrete. Although this element can model the interaction between concrete and bars very well, it loses precision because it presupposes identical degrees of freedom for all 4 sides around the joint element and ignores the shear deformation of joint planes. Another important point about the existing types of models is that most of them cannot be used for studying joints in different frame locations. Thus, most of them are useful for only one of various interior, exterior, or corner locations. In the present study, the beam-column element introduced by Limkatanyu and Spacone (2002a) was used
for modeling beam and column elements since it enjoys good precision and includes the interaction between the concrete and bars (Limkatanyu and Spacone, 2002b). A joint element was also defined and used, which, in addition to its flexibility in modeling different types of joint elements such as interior, exterior, corner, and footing, is capable of being assembled with the above beam-column element. Moreover, this modeling takes into consideration such factors as the bond-slip effect between the bars that pass through joints, the pull-out effect of bars that are restrained within joints, the nonlinear behavior of materials, and the shear-deformation effect of different beam-column elements. The introduced modeling is easy to use. In order to model the joint elements, a pull-out mechanism, an RC subelement, and a concrete subelement were first defined as the composing parts of the RC joint element. These parts were then assembled to produce 4 types of joint elements to be used along with beam-column elements in the modeling of RC moment-resisting frames. For simplicity's sake, RCF, RCMRF, BCE, JE, RCSE, and CSE are used in the text instead of reinforced concrete frame, reinforced concrete moment-resisting frame, beam-column element, joint element, reinforced concrete subelement, and concrete subelement, respectively.

Slip effect in reinforced concrete

The bond effect is an important factor in explaining local failures as well as the rates of energy absorption and of waste of the components of the inner force in RC members. A reduction in bond stress leads to the redistribution of internal forces. When, under the effect of applied forces, a crack in an RC member is created (Figure 1), cracks appear along with strain$\varepsilon S2$ on both sides of the member. On parts further from the crack

faces, the axial force of the bar is transferred to the concrete with the help of the bond stress. The value of the bond stress is zero in the inner parts of the transfer length (lt), and it is maximum on the crack faces. This means that there is no slip in the middle or central parts, which cover the distance between the 2 transfer lengths on the 2 sides ($L - 2lt$) (Kwak and Song, 2006).

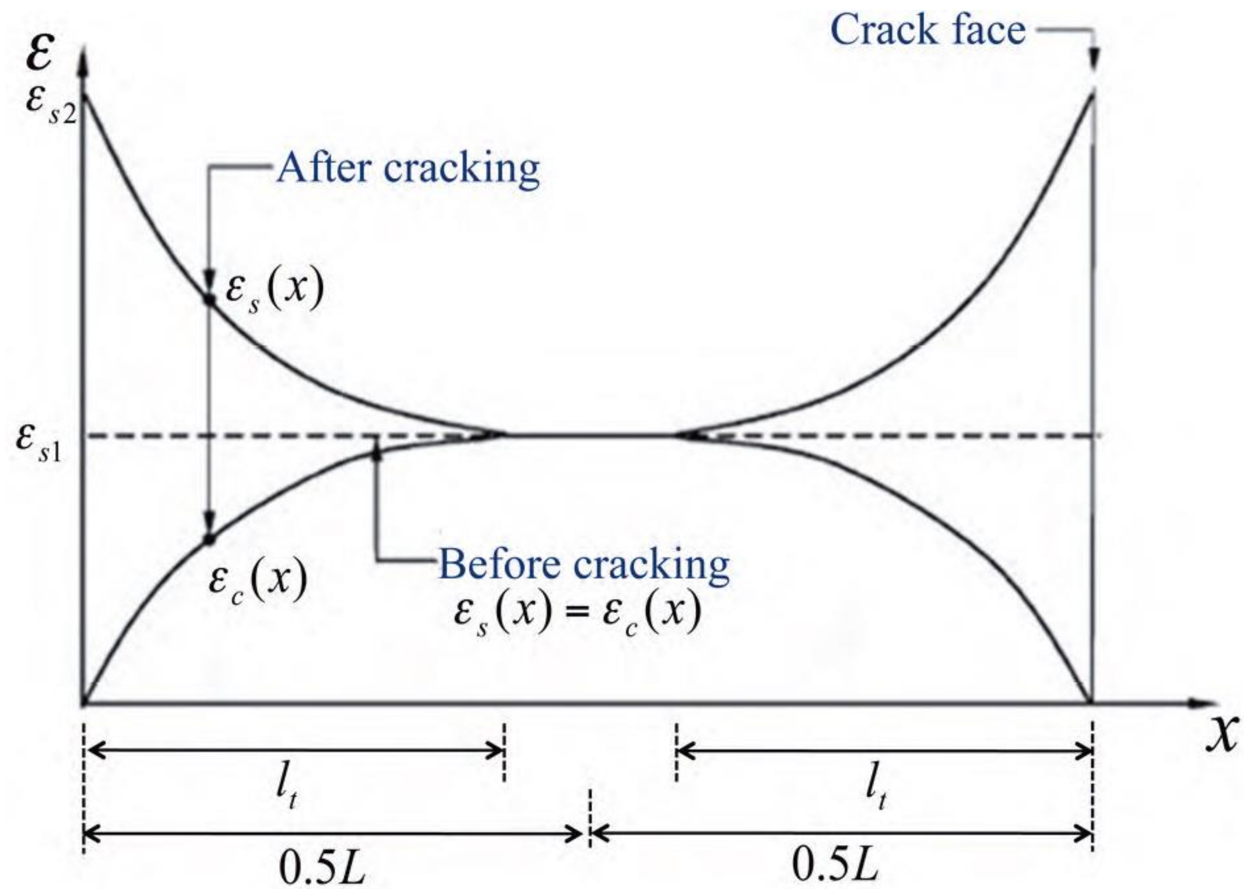

Figure 1. Strain distribution in cracked reinforced concrete (Kwak and Song, 2006).

It is assumed that after the occurrence of a crack, the strain values of the concrete and bar are the same at point $x = lt$ and are both $\varepsilon S1$. Based on the distribution of the strain, we may calculate the local slip by evaluating the difference between length variations of the bar and concrete at distance x from the crack face and the middle point of the cracked member ($x = L/2$), as shown in Eq. (1) (Kwak and Kim, 2006).

$$s(x) = \int_x^{L/2} (\varepsilon_s(x) - \varepsilon_c(x))dx \qquad (1)$$

In the above equation, L is the length of the distance between neighboring cracks, which is called the crack space. $\varepsilon S(x)$and$\varepsilon C(x)$ are the bar and concrete strain distributions, respectively. Considering the bond effect and the free body diagram of a length segment between the 2 cracks, and assuming the linearity of the equation of bond stress and slip as $\tau b = Eb * s(x)$, the function of slip distribution $s(x)$will be obtained in the form of Eq. (2).

$$\frac{d^2 s(x)}{dx^2} - k^2 s(x) = 0 \ , \ k^2 = m \sum\nolimits_0 E_b (1 + n\rho)/A_s E_s \ , \ n = \frac{E_s}{E_C} \ , \rho = \frac{A_s}{A_C} \qquad (2)$$

Eb is the slip modulus and is assumed to be 1.826×104 MN

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m3 by Kwak and Kim (2006). m is the number
of tensile bars and

$\bar{0}$ is the circumference of a bar section. The general answer to differential Eq. (2) will be in the form of Eq. (3).

$$s(x) = C_1 \sinh(x) + C_2 \cosh(x) \tag{3}$$

In the above equation, the $C1$ and $C2$ constants are calculated from boundary conditions. In the boundary conditions, the slip at $x = lt$ is zero, and at $x = 0$, which is the crack face, it is maximum ($S0$). It can be assumed that the crack width is twice as much as the maximum of $S0$ ($S0 = w/2$) (Kwak and Kim, 2006). Researchers have proposed some equations for calculating crack widths (Piyasena, 2002). For calculating the

transient length, experimental or analytical equations can be used based on the equivalent force of the RC element between the 2 cracks. After obtaining the specifications of the bond along the length of the member, we can evaluate the slip and stress distributions of the distance between 2 neighboring cracks.

Numerical investigation

As the first specimen, a one-bay, one-story frame was studied under the name of specimen 1, and the analytical results were compared with the corresponding experimental results. In numerical modeling, beams and columns are subdivided into a sufficient number of BCEs. Because the formulation is displacement-based and the response depends on the element size, the length of the BCE needs to be short enough. As a simple suggestion, the length of the BCE can be selected as equal to or smaller than the average crack spacing in the beam or column. In these cases, convergence will be achieved in the numerical results. The equation given by CEB-FIP (1978) was adopted for the calculation of average crack spacing. Specimen 1 was tested by Alin and Altin (2007) and was modeled as the combination of BCEs, JE type 1, and JE type 2. Some details are shown in Table 2 and Figure 11. Columns have no constant axial load and the loading is carried out laterally only.

For nonlinear solving of this model, a Newton-Raphson method that involved controlling displacement was used. In Figure 12, experimental results are compared with analytical ones produced in analyses 1-4 in a pushover status for specimen 1. In Figure 13, the results are compared in a cyclic status. Results show that in analysis 1, where the bond-slip effect and nonlinear behavior of the joint are not included, experimental results are very different from analytical ones. This difference is high for stiffness. By inserting the equivalent bond-slip effect in analysis 2, results become more accurate with regard to resistance but do not change much with respect to stiffness, especially the stiffness of unloading and reloading paths. In analysis 3, the analytical accuracy of calculated resistance and stiffness improves while no good agreement appears yet between the unloading and reloading paths, particularly in the final cycles. Analysis 4 makes for a considerable improvement in the results, and the analytical unloading and reloading paths are estimated with good precision. Thus, it can be said that this method enjoys a good accuracy in working out the members' resistance, stiffness, and real nonlinear behavior. As specimen 2, a column under lateral cyclic loading was investigated. This specimen had a constant axial load with a magnitude of 350 kN and was tested by Qiu et al (2002). Some details are shown in Table 3 and Figure 14. In numerical modeling, the specimen is modeled as the combination of 10 BCEs and type 1 of JEs. Figure 15 shows the result of analysis 4 and experimental load-displacement responses with very good similarity and precision for specimen 2. Thus, analysis 4 enjoys a good accuracy in working out the members' resistance and stiffness and during cyclic loading. In addition, due to the capabilities of nonlinear modeling of the JE, using analysis 4 and directly

implementing the bond-slip effect in calculations, we can study the analytical behavior of elements resulting from a decreased embedded length or reduction of the bond-slip effect in longitudinal bars. In Figure 16a, the analytical results of specimen 1 are provided, assuming that the columns' longitudinal bars are constrained 5 cm in the foundation. It should be added that, in the tested main model, the columns' longitudinal bars were continued 45 cm into the foundation and were not pulled out. Results reveal that by reducing the embedded length at the foot of a column, bars are increasingly pulled out of the foundation and, consequently, the lateral capacity of the frame will be lessened. Figure 16b presents a comparison of real experimental results with analytical ones for specimen 1, assuming that the bar-concrete bond-slip effect around the joint and the BCEs is weakened. The stress bond-slip relationship has been considered as linear with a slope of 5 MPa/mm. This slope signals a weak bond. According to the results, due to insufficiency of the bond between the concrete and bars, the stiffness of the RC elements decreases. This result is also revealed in the unloading and reloading paths.

Conclusion

According to the results, the presence or absence of the bond effect in numerical modeling and analysis will bring about considerably different results, including results for deformation and forces. When the bond-slip effect is excluded, the values for the stiffness of the elements and for internal forces appear to be higher than their real figures. Consequently, the values obtained for deformation and energy waste in the hysteresis circuits tend to be lower than the real values. All of the studied methods for inserting the bond-slip effect into the fiber model can relatively improve the accuracy of analytical results compared to experimental ones. The proposed method of this study has proved to enjoy the highest accuracy with regard to cyclic analysis. Among the features of the proposed method, we refer to its ability for modeling beam-column and JE nonlinear behavior separately. In addition, depending on the location of the JE in the RCF and its governing behavior feature, various types of joints can be utilized. Although compared to other studied methods the suggested method involves more numeric calculations and higher degrees of freedom in modeling, it enjoys a higher speed of modeling and less need for calculations compared to methods such as finite element modeling, implementing the bond-slip effect using contact (or link) elements. Moreover, the proposed method can be used in analyses that require high accuracy. In conclusion, the authors of this paper suggest that this method will be useful and remarkably accurate for the nonlinear cyclic analysis of RCMRF.